

$\Delta\Delta$ dibaryon structure in extended chiral $SU(3)$ quark model *

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The structure of $\Delta\Delta$ dibaryon is studied in the extended chiral $SU(3)$ quark model in which vector meson exchanges are included. The effect from the vector meson fields is very similar to that from the one-gluon exchange (OGE) interaction. Both in the chiral $SU(3)$ quark model and in the extended chiral $SU(3)$ quark model, the resultant mass of the $\Delta\Delta$ dibaryon is lower than the threshold of the $\Delta\Delta$ channel but higher than that of the $\Delta N\pi$ channel.

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Recently the chiral $SU(3)$ quark model [1] has been extended to include vector chiral fields [2-4]. Using this extended chiral $SU(3)$ quark model, the deuteron structure and $N - N$ scattering process were studied. In this extended chiral $SU(3)$ quark model, instead of the one gluon exchange (OGE) interaction, the vector meson exchanges play the dominate role in the short range part of the quark-quark interactions. Since dibaryon systems have small size, the short range behavior of the interaction must be important for the dibaryon structures [5,6]. In the work of Glozman et al [7,8], the vector meson coupling was also included to replace the OGE. It was pointed out that the spin-flavor interaction is important in explaining the energy of the Roper resonance, and a comparatively good fit to the baryon spectra was obtained.

Many works show that the $\Delta\Delta$ dibaryon (deltaron; $S = 3, J^\pi = 3^+$ and $T = 0$, where S is the spin, J the total angular momentum and T the isospin) is an interesting candidate of a nonstrange dibaryon. In 1987, Yazaki [9] analyzed systems with two nonstrange baryons in the framework of the cluster model where the OGE interaction and the confining potential between two quarks were considered. The result showed that among the NN , $N\Delta$, and $\Delta\Delta$ systems, the $\Delta\Delta$ system (deltaron with $S = 3, T = 0$) is the only system in which color magnetic interaction (CMI) between two clusters is attractive. Since the Δ is a resonance with a quite wide width and easily decays into $N\pi$, the deltaron might have a large width so that it cannot easily be detected in the experiment, even though it is a bound state of $\Delta\Delta$, except that its mass is below the threshold of the $NN\pi\pi$ channel. Wang et al. [10] studied the structure of the deltaron in terms of the quark delocalization model. They found that the deltaron is a deeply bound state with a binding energy of 320-390 MeV, namely, its energy level is below the threshold of the $NN\pi\pi$ channel. Yuan and Zhang et al. [11] also studied the structure of the deltaron in the chiral $SU(3)$ quark model, in which the OGE plays the

dominate role in the short range part of the quark-quark interactions. They found that the resultant mass of the Deltaron is lower than the threshold of the $\Delta\Delta$ channel but higher than that of the $\Delta N\pi$ channel.

In this paper, we study the structure of deltaron in the extended chiral $SU(3)$ quark model. The resonating group method (RGM) by solving a coupled-channel equation is used, where the $\Delta\Delta$ and CC (hidden color) channels are all included. In Sec. II, a brief introduction of the extended chiral $SU(3)$ quark model is outlined. The result is presented and discussed in Sec. III. A conclusion is drawn in Sec. IV.

In the extended chiral $SU(3)$ quark model, besides the nonet pseudo-scalar meson fields and the nonet scalar meson fields, the coupling between vector meson fields and quarks is also considered. With this generalization, the Hamiltonian of the system can be written as

$$H = \sum_i T_i - T_G + \sum_{i < j} V_{ij}, \quad (1)$$

and

$$V_{ij} = V_{ij}^{\text{conf}} + V_{ij}^{\text{OGE}} + V_{ij}^{\text{ch}}, \quad (2)$$

$$V_{ij}^{\text{ch}} = \sum_{a=0}^8 V^{s_a}(\vec{r}_{ij}) + \sum_{a=0}^8 V^{\text{ps}_a}(\vec{r}_{ij}) + \sum_{a=0}^8 V^{v_a}(\vec{r}_{ij}) \quad (3)$$

where $\sum_i T_i - T_G$ is the kinetic energy of the system, and V_{ij} includes all the interactions between two quarks. V_{ij}^{conf} is the confinement potential taken as quadratic form, V_{ij}^{OGE} is the OGE interaction, and V_{ij}^{ch} represents the interactions from the chiral field coupling, which, in the extended chiral $SU(3)$ quark model, includes the scalar meson exchange V_{ij}^s , the pseudo-scalar meson exchange V_{ij}^{ps} and the vector meson exchange V_{ij}^v potentials. In Eq.(2), the OGE is taken in the usual form [2], while the confinement potential is chosen in the quadratic form

$$V_{ij}^{\text{conf}} = -\lambda_i^c \cdot \lambda_j^c a_{ij}^{c0} - \lambda_i^c \cdot \lambda_j^c a_{ij}^c r_{ij}^2. \quad (4)$$

The quark-chiral field (scalar, pseudo-scalar and vector nonet mesons) induced interactions are eqs. (5-7)

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$$V^{sa}(\vec{r}_{ij}) = -C(g_{ch}, m_{sa}, \Lambda_c) X_1(m_{sa}, \Lambda_c, r_{ij}) \lambda_a(i) \lambda_a(j) + V_{sa}^{\vec{\ell}, \vec{s}}(\vec{r}_{ij}), \quad (5)$$

$$V^{psa}(\vec{r}_{ij}) = C(g_{ch}, m_{psa}, \Lambda_c) \frac{m_{psa}^2}{12m_{qi}m_{qj}} \{X_2(m_{psa}, \Lambda_c, r_{ij}) (\vec{\sigma}_i \cdot \vec{\sigma}_j) + \left(H(m_{psa} r_{ij}) - \left(\frac{\Lambda_c}{m_{psa}} \right)^3 H(\Lambda_c r_{ij}) \right) \hat{S}_{ij} \} \lambda_a(i) \lambda_a(j), \quad (6)$$

$$V^{va}(\vec{r}_{ij}) = C(g_{chv}, m_{va}, \Lambda_c) X_1(m_{va}, \Lambda_c, r_{ij}) \lambda_a(i) \lambda_a(j) + C(g_{chv}, m_{va}, \Lambda_c) \frac{m_{va}^2}{6m_{qi}m_{qj}} \left(1 + \frac{f_{chv}}{g_{chv}} \frac{m_{qi} + m_{qj}}{M_p} + \frac{f_{chv}^2}{g_{chv}^2} \frac{m_{qi}m_{qj}}{M_p^2} \right) \{X_2(m_{va}, \Lambda_c, r_{ij}) (\vec{\sigma}_i \cdot \vec{\sigma}_j) - \frac{1}{2} \left(H(m_{va} r_{ij}) - \left(\frac{\Lambda_c}{m_{va}} \right)^3 H(\Lambda_c r_{ij}) \right) \hat{S}_{ij} \} \lambda_a(i) \lambda_a(j) + V_{va}^{\vec{\ell}, \vec{s}}(\vec{r}_{ij}), \quad (7)$$

and M_p is a mass scale, taken as proton mass. The detailed formula expressions can be found in Ref. [1,2]. The coupling constant of the OGE and the strength of confinement potential are determined by the stability condition of N and mass difference between Δ and N . The parameters g_{ch} is the coupling constant for the scalar and pseudo-scalar chiral field couplings, which can be determined from experimental value. For vector meson nonet field coupling, the vector coupling and tensor coupling constants g_{chv} and f_{chv} are taken to be the same values as those used in the study of deuteron and NN phase shift [2]. The meson masses (m_{ps} , m_s , and m_v) are taken to be the experimental values. Only the mass of σ meson (m_σ) is treated as an adjustable parameter. The cut-off mass Λ is taken to be 1100MeV for all mesons. All parameters used here are shown in Table 1, which are determined in the NN scattering calculation by fitting the binding energy of deuteron.

We choose the two-cluster configuration as the dibaryon's model space [11-13]. The CC channel has the form

$$|CC\rangle = -\frac{1}{2}|\Delta\Delta\rangle + \frac{\sqrt{5}}{2}A_{STC}|\Delta\Delta\rangle \quad (8)$$

where A_{STC} stands for the antisymmetrizer in the spin-isospin-color space.

In our present calculation, the mixture of the $L = 0$ and $L = 2$ states which shows the effects of the tensor forces in OGE and chiral field induced potentials are also considered, namely, the two-channel-four-state, $\Delta\Delta(L = 0)$, $\Delta\Delta(L = 2)$, $CC(L = 0)$, and $CC(L = 2)$, calculation is performed [11-14].

TABLE I: Model parameters and the the corresponding binding energies B_{deu} of deuteron.

| | Chiral $SU(3)$ quark model | Extended chiral $SU(3)$ quark model | |
|--------------------|-------------------------------|--|--------|
| | | set I | set II |
| $b_u(fm)$ | 0.5 | 0.45 | 0.45 |
| $g_{NN\pi}$ | 13.67 | 13.67 | 13.67 |
| g_{ch} | 2.621 | 2.621 | 2.621 |
| g_{chv} | 0 | 2.351 | 1.972 |
| f_{chv}/g_{chv} | 0 | 0 | 2/3 |
| $m_\sigma(MeV)$ | 595 | 535 | 547 |
| g_u | 0.886 | 0.293 | 0.399 |
| $\alpha_s(g_u^2)$ | 0.785 | 0.086 | 0.159 |
| $a_{uu}(MeV/fm^2)$ | 48.1 | 48.0 | 42.9 |
| $B_{deu}(MeV)$ | 2.13 | 2.19 | 2.14 |

In the coupled-channel bound-state calculation, one must carefully eliminate forbidden states, which may spoil the numerical calculation. In the deltaron case, there exists a state, which has the zero eigenvalue of the normalization operator $\langle N \rangle = 0$ due to the Pauli blocking effect. It reads

$$|\Psi\rangle_{\text{forbidden}} = |\Delta\Delta\rangle - \frac{1}{2}|CC\rangle. \quad (9)$$

Performing an off-shell transformation, this nonphysical degree of freedom can be eliminated and the reliable result can be achieved.

By using the model parameters shown in Table I, the NN scattering phase shifts and the binding energy of deuteron can be well reproduced [2]. Here we use the same sets of parameters to study the structure of deltaron. The calculated binding energies of deltaron and the corresponding root-mean-square radius (rms) in the extended chiral $SU(3)$ quark model are listed in Table II. In order to compare the result with other model calculations, the results of the chiral $SU(3)$ quark model [1] are also given in Table II. The results of the extended chiral $SU(3)$ quark model for two different cases are shown. one is no tensor coupling of the vector mesons with $f_{chv}/g_{chv} = 0$ (set I), another involves tensor coupling of the vector mesons with $f_{chv}/g_{chv} = 2/3$ (set II). The calculation is carried out in four different combinations: $\Delta\Delta$ ($L = 0$), $\Delta\Delta$ ($L = 0$ and 2), $\Delta\Delta + CC$ ($L = 0$), and $\Delta\Delta + CC$ ($L = 0$ and 2).

It is shown that the binding energy of the deltaron is indeed lower than the threshold of the $\Delta\Delta$ channel, which is always several tens MeV in all cases. Since the deltaron mass is still higher than the mass of $N\Delta\pi$, the deltaron seems not to be a narrow width dibaryon.

Our calculation shows that the channel coupling effect is much larger than the L state mixing effect, which are all caused by the tensor interaction. The largest binding

TABLE II: Binding energy B and rms \bar{R} of the deltaron $B = -(E_{\text{deltaron}} - 2M_\Delta)$, $\bar{R} = \sqrt{\langle r^2 \rangle}$.

| | | $\Delta\Delta(L=0)$ | $\Delta\Delta \begin{pmatrix} L=0 \\ +2 \end{pmatrix}$ | $\Delta\Delta_{CC}(L=0)$ | $\Delta\Delta_{CC} \begin{pmatrix} L=0 \\ +2 \end{pmatrix}$ |
|-----------------------------------|------------------------|---------------------|--|--------------------------|---|
| Chiral SU(3) quark model | $B(\text{MeV})$ | 23.0 | 29.1 | 40.6 | 48.3 |
| | $\bar{R}(\text{fm})$ | 0.98 | 0.96 | 0.88 | 0.88 |
| Extended chiral SU(3) quark model | set I $B(\text{MeV})$ | 56.1 | 62.4 | 78.2 | 84.0 |
| | $\bar{R}(\text{fm})$ | 0.80 | 0.80 | 0.76 | 0.76 |
| | set II $B(\text{MeV})$ | 41.7 | 48.0 | 64.7 | 70.4 |
| | $\bar{R}(\text{fm})$ | 0.84 | 0.84 | 0.78 | 0.78 |

energy of deltaron appears in the extended chiral SU(3) model in the case of set I. It means that the vector chiral fields offer substantial attractions across two Δ clusters, so that the deltaron becomes more bound. The tensor coupling from vector fields in the case of set II in the extended chiral SU(3) model will reduce ~ 14 MeV in the deltaron binding energy as compared to that in set I case.

It is shown from Table 1 that the coupling constant of the OGE is greatly reduced when the vector meson field coupling is considered. The coupling constant α_s of the OGE between $u(d)$ quarks is determined by fitting the mass difference between Δ and N . For both parameters shown in the set I and the set II cases, $\alpha_s < 0.2$ which is much smaller than the value (0.78) used in the chiral SU(3) quark model. The results manifest that the OGE interaction is quite weak in the extended chiral SU(3) quark model. Instead of the OGE, the vector meson exchanges play dominate role in the short range part of the interaction between two quarks, so that the mechanism of the quark-quark short range interaction of the two models is totally different. The quark-quark short range interaction is from the OGE in the chiral SU(3) quark model, while it is mainly from vector meson exchanges in the extended chiral SU(3) quark model. Furthermore, The binding energy of deltaron in the extended chiral SU(3) quark model is quite similar as that of the chiral SU(3) quark model. The results tell us that no matter whether the OGE or the vector meson exchange controls the quark-quark short range interaction, the main properties of deltaron keep unaffected. In addition, it is also shown from the calculation that the tensor coupling of the vector chiral field reduces the binding energies of deltaron.

In summary, the vector meson exchange effect on deltaron in the extended chiral SU(3) quark model is studied. The model space is enlarged to include the CC channel. The contributions from various chiral fields are included. The results show that the binding energy of the deltaron is still ranged around several tens MeV when the vector meson exchanges dominate the short range part of

the quark-quark interaction. Our results show that the mass of the deltaron is always smaller than that of $\Delta\Delta$, but larger than that of $\Delta N\pi$, which are quite similar to those of the chiral SU(3) quark model.

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